ANL-HEP-CP-96-33

May 1, 1996

ASSOCIATED PRODUCTION OF CHARM AND A HARD PHOTON

B. Bailey[a], E. L. Berger[b] and L. E. Gordon[b]

[a] *Physics Department, Eckerd College, St. Petersburg, FL 33711, U.S.A.*

[b] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, U.S.A.*

ABSTRACT

The two particle inclusive cross section for the reaction $p + \bar{p} \rightarrow \gamma + c + X$ is studied in perturbative quantum chromodynamics at order $O(\alpha_s^2)$, for large values of the transverse momentum of the prompt photon and charm quark. Two different techniques are used in performing the phase-space integrals; the first is purely analytical, and the second is a combination of analytic and Monte Carlo integration methods. The second, more versatile technique facilitates imposition of photon isolation restrictions and other selections of relevance in experiments. Differential distributions are provided for various observables, and a comparison is made with preliminary data from the CDF collaboration.

Invited talk presented by L. E. Gordon at the XXXI st Rencontres de Moriond, 'QCD and High Energy Hadronic Interactions' March 23-30, 1996, Les Arcs, France

1. Introduction

The observation of a photon carring a large transverse momentum, p_T, among the final state products of a high energy hadronic reaction has long been regarded as a powerful tool for gathering information about the short distance dynamics of these reactions, primarily because photons couple directly to quarks via the point-like electromagnetic interaction. Single prompt photon production has been studied extensively, both theoretically and experimentally, and has provided useful information about hadronic structure, in particular the gluon structure function of the proton. Data are beginning to appear from the study of the production of a prompt photon (γ) in association with a heavy quark whose transverse momentum balances a substantial portion of that of the photon. This two-particle inclusive reaction is particularly interesting because it offers the possiblility of a detailed study of the underlying QCD dynamics such as, e.g., rapidity correlations. In addition, it may provide a direct measurement of the charm content of the proton.

We report here on two next-to-leading order perturbative QCD calculations we have done of the reaction $p + \bar{p} \to \gamma + c + X$ at high energy [1,2]. In these calculations two different techniques are used in performing the phase-space integrals. In the first, purely analytical techniques are used. In the second approach, we use a combination of analytical and Monte Carlo techniques, which is more flexible and allows implementation of isolation cuts and other experimentally relevant selections. To warrant use of perturbation theory and the massless approximation, we limit our considerations to values of transverse momenta of the photon and charm quark $p_T^{\gamma,c} > 10$ GeV.

Only one *direct* hard scattering subprocess contributes in leading order: the quark-gluon Compton subprocess $gc \to \gamma c$. The initial charm quark and the initial gluon are constituents of the initial hadrons. In addition, there is a leading order *fragmentation* process in which the photon is produced from quark or gluon fragmentation, e.g., $gg \to c\bar{c}$ followed by $\bar{c} \to \gamma X$, or $qc \to qc$ followed by $q \to \gamma$. At next-to-leading order in QCD, several subprocesses contribute to the $\gamma + c + X$ final state: $gc \to gc\gamma$, $gg \to c\bar{c}\gamma$, $q\bar{q} \to c\bar{c}\gamma$, $qc \to qc\gamma$, $\bar{q}c \to \bar{q}c\gamma$, $c\bar{c} \to c\bar{c}\gamma$, and $cc \to cc\gamma$. A full next-to-leading order calculation requires the computation of the hard-scattering matrix elements for these two-to-three particle production processes as well as the one-loop $O(\alpha_s^2)$ corrections to the lowest order subprocess $gc \to \gamma c$. At $O(\alpha_s^2)$ there are, in addition, fragmentation processes in which the hard-scattering two-particle final-state subprocesses $c + g \to \gamma + c, c + \bar{c} \to \gamma + g$ and $q + \bar{q} \to \gamma + g$ are followed by fragmentation processes $c \to cX$, in the case of the first subprocess, and $g \to cX$ in the cases of the last two. These should be included because we factor the collinear singularities in the corresponding three-body final-state processes into non-perturbative fragmentation functions for production of a charm quark from a particular parton.

We are interested in the two-particle inclusive differential cross section, $E_\gamma E_c d\sigma/d^3p_\gamma d^3p_c$, where (E,p) represents the four-vector momentum of the γ or c quark. For each contributing subprocess, this calculation requires integration over the momentum of the unobserved final parton in the two-to-three particle subprocesses (g, $\bar{c}, q$, or $\bar{q}$). Collinear singularities must be handled analytically by dimensional regularization and absorbed into parton momentum densities or fragmentation functions.

2. Analytic Calculation

In our purely analytical calculation[1], we must integrate over enough of the phase-space analytically in order to cancel all soft and collinear singularities. This procedure imposes technical limitations such that it is not possible to obtain the fully differential two-particle cross section. We calculate instead the cross section $d\sigma/dp_T^\gamma dy^\gamma dz$, where the variable z is defined by

$$z = -\frac{p_T^\gamma . p_T^c}{(p_T^\gamma)^2}. \tag{1}$$

This definition indicates that z contains information on the transverse momentum of the charm quark, but no information on its rapidity y^c. Moreover, it is not possible to implement isolation cuts on the photon in the purely analytic calculation. Nevertheless the calculation is valuable for obtaining the relative importance of the various subprocess contributions and the overall the size of the cross section, as well as for checking aspects of the more versatile Monte Carlo calculation.

We calculate the cross section $d\sigma/dp_T^\gamma dy^\gamma dz$. Whenever the charm quark and photon have balancing values of p_T then $z = 1$. This occurs

1. for the leading order process $cg \to \gamma c$,
2. for the virtual gluon exchange processes,
3. whenever a gluon becomes soft in the three-body processes, or
4. when a third parton becomes collinear to the beam in a three-body process.

The point $z = 1$ is associated with various soft and collinear poles, and in order to expose these poles all phase-space integrals are carried out in $4 - 2\epsilon$ dimensions. The poles are exposed by expanding the results in $(1-z)$. The analytical cross section is expressed in terms of distributions in $(1-z)$ such as $1/(1-z)_+$ and $\delta(1-z)$. In addition whenever the final state photon becomes collinear to a final state quark, the resulting singularity must be exposed in a similar way before it is absorbed into the photon fragmentation function. This singularity occurs at another value of z, ($z = z_1$). This means that there are also distributions in $(z-z_1)$. The cross section is singular at $z = 1$ and $z = z_1$, but the singularities are integrable through

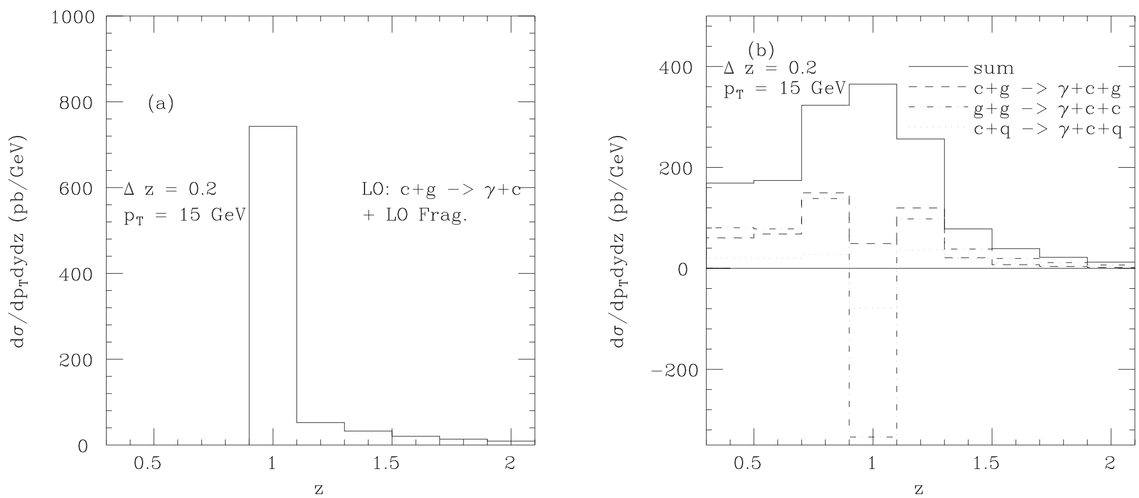

Fig. 1. Cross section as a function of z at $y^\gamma = 0$ in (a) leading order and (b) next-to-leading showing the dominant contributions.

the use of 'plus'-distributions. The cross section is presented in terms of integrals over finite regions of z such as

$$\begin{aligned} \frac{d\sigma}{dp_T^\gamma dy^\gamma dz} &= \frac{1}{\Delta z}\int_{z-\frac{\Delta z}{2}}^{z+\frac{\Delta z}{2}} \frac{d\sigma}{dp_T^\gamma dy^\gamma dz'}dz'; \\ \frac{d\sigma}{dp_T^\gamma dy^\gamma} &= \int_{z_a}^{z_b} \frac{d\sigma}{dp_T^\gamma dy^\gamma dz'}dz'. \end{aligned} \tag{2}$$

Our results are presented at a center-of-mass energy $\sqrt{s} = 1.8$ TeV. The analytical results are obtained with the GRV parametrization of the proton parton densities, and all renormalization/factorization scales are taken as $\mu = p_T^\gamma$. Up to 30% differences are observed if the CTEQ3M parton distributions are used. We sum over charm and anticharm production throughout. In Fig.1a the net lowest order contribution is shown as a function of z at $p_T^\gamma = 15$ GeV and for a bin size $\Delta z = 0.2$. The lowest order cross section is made up of the lowest order direct term $cg \rightarrow \gamma c$, which is proportional to $\delta(1-z)$ and provides the peak at $z = 1$, plus the various photon fragmentation contributions which contribute in the region $z \geq 1$. The most significant feature of this curve is that there is no contribution to the cross section in the region $z \leq 1$. This unrealistic prediction shows the inadequacy of the lowest order predictions.

Figure 1b shows the distribution in z predicted by the next-to-leading order calculation. The next-to-leading order contributions serve to lower the peak at $z = 1$, and they broaden the distribution. The cross section is finite at all values of z, closer to the situation observed in experiments. In addition, in Fig.1b we display contributions from the most important subprocesses. The cg initiated process dominates the cross section, but there are important

contributions from the gg and cq initiated process in the low p_T^γ region.

3. Monte Carlo Calculation

The combination of analytic and Monte Carlo techniques used here to perform the phase space integrals is documented and described elsewhere[2]. The analytic/Monte Carlo method allows for the calculation of many different observables without much extra effort and for the imposition of experimental cuts. In collider experiments a photon is observed and its momentum is well measured only when the photon is isolated from neighboring hadrons. In our calculation, we impose isolation in terms of the cone variable R:

$$\sqrt{(\Delta y)^2 + (\Delta \phi)^2} \leq R. \tag{3}$$

In Eq. (3), Δy ($\Delta\phi$) is the difference between the rapidity (azimuthal angle in the transverse plane) of the photon and that of any parton in the final state. The photon is said to be isolated in a cone of size R if the ratio of the hadronic energy in the cone and the transverse momentum of the photon does not exceed $\epsilon = 2\text{GeV}/p_T^\gamma$. We show distributions for the choice $R = 0.7$ typical of current experiments.

The structure of the QCD hard-scattering matrix element produces *positive* correlations in rapidity at collider energies. To examine these correlations more precisely, in Fig. 2a, we display the differential cross section in y^c, for two intervals of y^γ in the forward rapidity region. These distributions show that the typical rapidity of the charm quark follows that of the photon, and thereby confirms the positive correlation between the rapidities of the photon and charm quark. In Fig.2b we compare our results to CDF data[3] for photon plus $\mu^\pm$ production. The three upper points are obtained[4] from the Monte Carlo event generator Pythia whereas the lower point is that given by our theoretical calculation. The Pythia results lie substantially below the data whereas our results are higher than the data but somewhat closer to it.

4. Conclusions

We presented the results of two calculations of the inclusive production of a prompt photon in association with a heavy quark at large values of transverse momentum. Both analyses are done at next-to-leading order in perturbative QCD. Our results agree quantitatively as they should, but the combination of analytic and Monte Carlo methods is more versatile. We provide differential cross sections in transverse momenta and rapidity, including photon isolation restrictions, that should facilitate contact with experimental results at hadron collider energies. We show that the study of two-particle inclusive distributions, with specification of the momentum variables of both the final prompt photon and the final heavy quark, tests correlations inherent in the QCD matrix elements and should provide a means

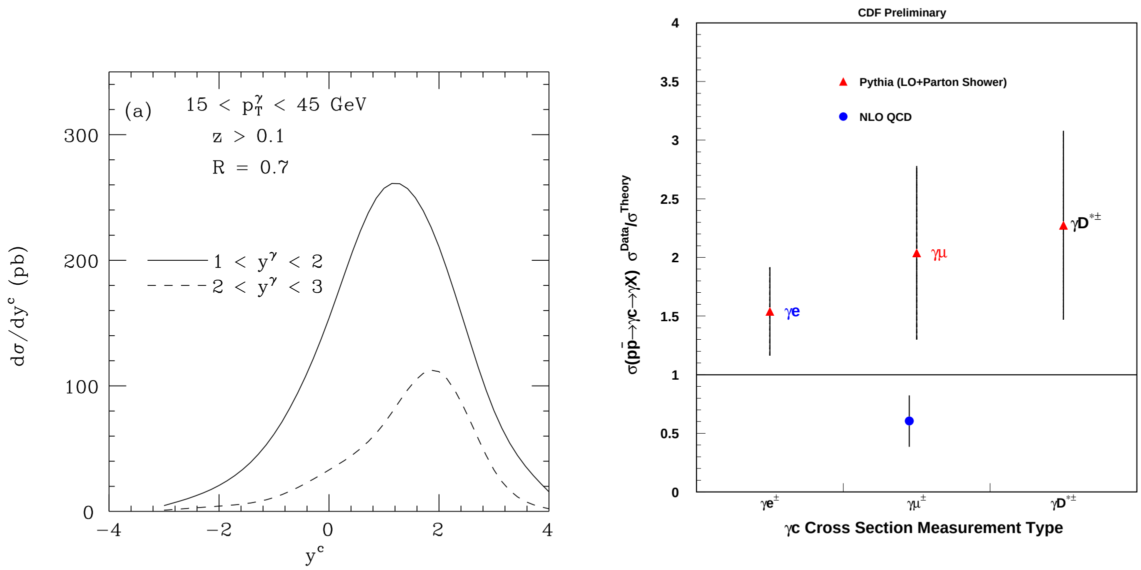

Fig. 2. (a)Cross section $d\sigma/dy^c$ as a function of the rapidity of the charmquark for $p+\bar{p}\to\gamma+c+X$ at $\sqrt{s}=1.8$ TeV. The solid curve shows the result when the photon rapidity is restricted to $1.0 < y^\gamma < 2.0$, and the dashed curve displays the result for $2.0 < y^\gamma < 3.0$. (b) Ratio of the measured cross section to that predicted by theory for various final state charm decay products.

for measuring the charm quark density in the nucleon. A comparison of our next-to-leading predictions with the preliminary CDF data shows reasonable agreement.

The work at Argonne National Laboratory was supported by the US Department of Energy, Division of High Energy Physics, Contract number W-31-109-ENG-38. This work was supported in part by Eckerd College.

5. References

[1] E. L. Berger and L. E. Gordon, Argonne report ANL-HEP-PR-95-36 (hep-ph /9512343), Phys. Rev. **D** (in press), and references therein.

[2] B. Bailey, E. L. Berger and L. E. Gordon, Argonne report ANL-HEP-PR-95-87 (hep-ph/9602373), submitted to Phys. Rev. **D**, and references therein.

[3] CDF Collaboration, R. Blair *et al*, Proceedings of the 10th Topical Workshop on Proton-Antiproton Collider Physics, May, 1995 (AIP Conference Proceedings 357), edited by R. Raja and J. Yoh (AIP Press, N.Y., 1996), pp 557-567.

[4] S. Kuhlmann, CDF Collaboration, private communication.